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TITLE

Rapid deglaciation of the last ice sheet in the Grampian Mountains, Scotland.

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ABSTRACT

Towards the end of the Late Devensian glaciation, ice sourced from the Western Grampian Mountains of Scotland flowed down Strath Spey to encroach on the northern flanks of the Cairngorm Mountains. The maximum of this late advance and its subsequent retreat is recorded by moraines, ice-marginal meltwater channels, and kame terraces that can be traced up Strath Spey for 60 km from its down-valley limit. New cosmogenic ^{10}Be exposure ages from moraines indicate deglaciation at 15.0 ± 0.6 ka. This timing matches closely existing age data for deglaciation of the eastern Cairngorm plateau and for other sites along Strath Spey. The implication is that active ice retreat from the flanks of Strath Spey occurred within the ~1 ka uncertainty of the cosmogenic exposure ages. Initial ice retreat occurred under cold conditions at the end of Greenland Stadial 2a (GS-2a) (16.9-14.7 ka). We suggest the advance followed the collapse of the marine parts of the British-Irish Ice Sheet at ~ 16ka. The combination of increased precipitation at a time of low temperatures would cause an advance. The rapidity of deglaciation may reflect enhanced Föhn effects caused by the ice dome in the Western Highlands.

KEY WORDS

Deglaciation; British-Irish ice sheet; Strath Spey; ^{10}Be cosmogenic exposure ages; climate.

INTRODUCTION

The sequence and timing of events during deglaciation of the last ice sheet in Scotland remain poorly constrained. Strath Spey forms a major topographic corridor through the Grampians, flanked by the Monadhliath and Cairngorm Mountains (Fig. 1). During the Pleistocene, powerful flows of ice were directed along Strath Spey from Rannoch Moor, the major snow and ice accumulation basin in the western Highlands for the Scottish ice sheet, and towards the inner Moray Firth, one of the major outlets of the ice sheet to the North Sea basin. The Cairngorm granite massif supported an independent ice centre. During the last, Late Devensian glaciation, the carry of schist erratics shows that Strath Spey ice encroached to elevations above 800 m on the northern flanks of the Cairngorms (Sugden, 1970; Hall and Phillips, 2006). This erratic limit is associated with the highest set of a remarkable, off-lapping assemblage of ice-marginal landforms found on the mountain flanks that includes lateral moraines, kame terraces and meltwater channels (Fig. 1B) (Hinxman and Anderson, 1915; Gordon, 1993). The ice-marginal forms cover an altitudinal range of ~500 m and can be traced for ~60 km along Strath Spey (Fig. 1A). Hence this landform assemblage provides an unusual opportunity to establish the pattern and timing of the final retreat of a major ice lobe within the last Scottish ice sheet.

Three conflicting models currently exist for deglaciation in Strath Spey in which the ice lobe (i) decayed passively, with slow down-wasting and final downwasting leading to the generation of huge volumes of meltwater (Sugden, 1970; Young, 1975), (ii) remained active during a slow retreat interrupted by long stillstands when large ice-dammed lakes developed at the ice margin (Hinxman and Anderson, 1915; Brazier et al., 1998; Everest and Kubik, 2006) and (iii) remained active but retreated rapidly with only brief stillstands. These conflicting models exist in part because of conflicting dating evidence. While cosmogenic exposure ages for boulders on moraines appear to support a prolonged stillstand at ca. 14.5–14.0 ka (Everest and Kubik, 2006) ages obtained on postglacial rockslides (Ballantyne et al., 2009) and basal radiocarbon dates (Sissons and Walker, 1974; Everest and Kubik, 2006) indicate that deglaciation was complete before ca. 15.5–15.0 ka (Ballantyne, 2010). This study provides a revised interpretation of the landform assemblage associated with the Strath Spey ice lobe in the northern Cairngorms as the product of a late advance of the last ice sheet and of its subsequent down wastage. The study reports new cosmogenic ^{10}Be exposure ages for boulders from moraines in the northern Cairngorms that constrain the time interval for deglaciation to the close of Greenland Stadial 2a (GS-2a) (16.9-14.7 ka).

STUDY AREA

The study area forms part of the northern flank of the Cairngorm Mountains and includes the prominent ridge of Sròn a’ Cha-no that separates Glen More from Strath Nethy (Fig. 2). The high ground is developed in the Caledonian Cairngorm Granite, with Moine psammitic schists forming the floor of the Glen More basin (Fig. 2). A remarkable assemblage of ice-marginal features is developed along the flanks of Strath Spey (Barrow et al., 1913; Hinxman and Anderson, 1915; Charlesworth, 1956), marking the final up-valley retreat of the Spey glacier and its attendant down wasting (Figs. 2 and 3). Many ridges that project towards the valley axis are notched by rock-cut meltwater channels (Bremner, 1934a; Gheorghiu et al., 2012). Re-use of many of these channels during deglaciation as routeways for ice-marginal meltwater is indicated where the channels are in sub-parallel sets, with channel floors sloping down valley, and associated with nearby ice-marginal features such as moraines and kame terraces (Hinxman and Anderson, 1915; Greenwood et al., 2007). Many tributary valleys entering Strath Spey from the Cairngorms and Monadhliath were blocked by ice lobes that built up moraines and dammed meltwater in ice-marginal lakes and ponds (Hinxman and Anderson, 1915; Bremner, 1934a; Brazier et al., 1998; Boston, 2013). Off-lapping, ice-marginal landforms can be traced along hill slopes for long distances on both the Cairngorm (Fig.2) and Monadhliath flanks of Strath Spey. The ice-marginal landforms descend in altitude towards the north-east towards likely ice limits marked by moraines at the confluence of the Avon and Livet and north-east of Grantown (Bremner, 1934b).

Within the study area, ice-marginal features record the extent of Strath Spey ice and its subsequent unzipping from Cairngorm ice (Fig. 4). The maximum of the advance is recorded by a trimline, with stripped granite surfaces below, and a small lateral meltwater channel at 832 m on Sròn a’ Cha-no (Figs. 1B and 2B). The sharpness of the morphological contrasts above and below the trimline, the lateral continuity and the relationship to ice flow from the west all point to the limit representing an advance along Strath Spey. In Coire Laogh Mòr and southwards towards Coire na-Ciste, lateral moraine ridges and channels and an upper limit for schist erratics occur at the slightly lower elevation of 810 m. From the col between Sròn a’ Cha-no and Stac na h-Iolaire, sloping, schist-bearing moraines extend into Strath Nethy (Fig. 3A). Lateral moraines from both Spey and Nethy ice meet near the base of the western wall of Strath Nethy and demonstrate the contemporaneity of the two ice masses (Fig. 4). Extensive granite boulder accumulations derived from rock slope failures also occur on the valley floor in upper Strath Nethy (Ballantyne et al., 2009). The lobate form of ridges on the surface of the boulder accumulations suggests deposition on to glacier ice, followed by glacial transport a short distance down the valley (Sugden and Clapperton, 1975). Residual Nethy ice on the valley floor also may have supported the eastern flanks of large, steeply-sloping fan deltas that extend downslope from the col (Fig. 3A). Horizontal benches cut in bedded gravel and sand on lower valley slopes (Fig. 3A) indicate that Spey ice blocked the outlet of Strath Nethy and so ponded ephemeral lakes between the separating ice margins. The fan deltas were fed by two main sets of meltwater channels in the col, a southern set with an intake at 725 m and a deeper northern set with an intake at 650 m (Fig. 3B). The moraine M1 at 720 m marks the presence of Spey ice at a time when the lower channels continued to pass meltwater through the col. After the ice surface dropped below the level of the Iolaire col, meltwater was diverted northward and sequences of lateral channels, some associated with the M2 and M3 moraines at 600 and 540 m respectively (Fig. 3B), mark the down wasting of the ice margin in Glen More.

DATING METHODS

In order to constrain the age of the deglaciation in the study area, samples were collected for cosmogenic exposure dating from seven large boulders, including sites on moraines M1-M3, and two bedrock sites at elevations of 741 to 540 m O. D. on the western slopes of Sròn a' Cha-no (Fig. 1B)(Table 1).

^{10}BE SAMPLE PREPARATION AND MEASUREMENT

Whole rock samples were crushed then sieved and the magnetic fraction removed from the 250 – 710 um fraction before being prepared as AMS (Accelerator Mass Spectrometry) targets following the standard procedures outlined in Binnie et al. (2015). The targets were measured at CologneAMS (Dewald et al., 2013), normalized to the standards of Nishiizumi et al. (2007). ^{10}Be concentrations shown in Table 2 include the subtraction of reagent blanks prepared alongside the samples. Analytical uncertainties are derived by summing in quadrature the 1 σ uncertainty of the AMS results with an estimated 1% uncertainty in the mass of the 9Be spike of both the samples and blanks. Exposure ages are estimated using the CRONUS-Earth calculator version 2.2, using version 2.2.1 of the constants file and Balco et al. (2008) and the Dunai (2001) 'Du' scaling. We used a local production rate ~~of~~ calibrated from a Lateglacial Interstade age for moraines in NW Scotland (NWHLPR11.6; Ballantyne and Stone, 2012). This production rate (4.39 ± 0.15 atoms/g/a at HLSL using Dunai, 2001, scaling) is in good agreement with the estimate of Small and Fabel (2015) from Glen Roy, based on the ^{10}Be ages of palaeoshorelines independently dated using a varve chronology. Where other, previously published ages are compared with our results, they have been recalculated using the local production rate calibration data set NHWLPR11.6 of Ballantyne and Stone (2012) and scaled according to Dunai (2001). Where the recast ages are reported, we note the erosion rate (e) used in the age derivation. Sample site coordinates and elevations were recorded using handheld GNSS. Topographic shielding factors for each sample site were measured in the field. We assumed a bulk rock density of 2.6 g/cm^3 and employed the std pressure flag and 07KNSTD AMS standard flag in the CRONUS-Earth calculator (Table 2).

Erosion rates. For CG12-004 the erosion rate is effectively zero because the surface of the projecting quartz vein was glacially polished. At this site, the projection of the quartz vein due to postglacial erosion indicates erosion rates on granite of 4.1 mm/ka. This is a high rate compared to the average rate of erosion on the Cairngorm Granite of 1.6 ± 0.6 mm/ka Phillips et al., (2006) derived from upstanding quartz veins (n=74). The high erosion value reflects weakening of the granite due to late stage hydrothermal alteration near the schist contact. Other samples were collected from boulders with macroscopically fresh surfaces and the average rate of erosion of 1.6 mm/ka is applied to those samples.

RESULTS

The results of surface exposure dating using ^{10}Be are summarized in Table 2. Age uncertainties at ± 1σ are given as both internal uncertainties, for between-sample comparison, and total (external) uncertainties. The latter incorporate ^{10}Be production rate uncertainties, and are appropriate for comparison with exposure ages obtained in other studies, and with radiocarbon dates. The ages presented below are those using the production rate scaling of Dunai (2001) and total uncertainties are employed throughout.

The exposure ages exhibit significant within-site variation. Boulders at or above the M1 moraine elevation include an outlier sample, CG14-001, with a exposure age of 24.0 ± 1.3 ka, which is interpreted as reflecting nuclide inheritance. Sample CG12-004 comes from a glacially-polished quartz vein surface that has experienced no postglacial erosion and provided an exposure age of 16.6 ± 1.0 ka. This date and the overlapping age on sample CG14-02 appear to require implausibly early deglaciation of an area close to one of the main centres of the last Scottish ice sheet and so may mark an earlier phase of glacial erosion or, alternatively, include slight nuclide inheritance. The three overlapping youngest age ranges from the elevation of the M1 moraine comprising two boulder samples and one bedrock sample together give an error weighted mean age of 14.4 ± 0.5 ka. The significant age difference with CG12-004 and CG14-02 make it unlikely that these ages relate to the same event. A single boulder on the M2 moraine provided an exposure age of 15.8 ± 0.9 ka. Two boulders on the M3 moraine give a mean age of 14.3 ± 0.6 ka. Error weighted mean ages for moraine ridges M1 and M3 between 720 and 540 m are the same and indicate that ice down wastage by ≥200 m occurred at 15.0 ± 0.6 ka.

DISCUSSION

The landform assemblage found in the study can be traced for ~60 km along Strath Spey (Fig. 5). The maximum limit down-valley is probably marked by the large moraines at the Avon-Livet confluence and in the Allt Bhreac, north-east of Grantown (Bremner, 1934b). The huge outwash terraces at Bridge of Avon (Bremner, 1934b) were also probably constructed as meltwater carried debris down the Avon from the ice margin. The M1 limit along the eastern side of the Dorback and Abernethy basins is clearly delineated by ice marginal channels, moraines and kame terraces (Hinxman and Teall, 1896; Hinxman and Anderson, 1915; Bremner, 1934a) (Fig. 2). The absence of moraines and channels east of the limit here and the discharge of meltwater through a col at 700 m into the Water of Caiplich (Fig. 2) indicate that Cairngorm ice had receded towards the Cairngorm plateau before Spey ice advanced to its maximum limit. This is consistent with morphological evidence from moraines on the flanks on the Sròn a' Cha-no being ice-free at this stage (Fig. 4). Further south, Strath Spey and Cairngorm ice were probably initially in contact at the line marked by the upper limit of schist erratics on the flanks of the northern Cairngorms (Fig 2). The development of the large moraines and ice marginal lakes in the Lairig Ghru and Gleann Einich occurred after unzipping of the two ice masses. Moraine M3 marks a former ice margin that can be traced up-valley to large moraines found at slightly higher elevations west of the ski car park above Glen More (Fig. 3C) and at the mouth of the Lairig Ghru. The M3 moraine however stands above the level of the moraines in Gleann Einich (Fig. 5). Marginal meltwater channels on the Monadhliath flank document the further retreat of ice up Strath Spey to beyond Laggan (Young, 1977; Young, 1978; Merritt et al., 2013) (Fig. 5).

Exposure ages from the study area can be compared to existing cosmogenic data. On the Cairngorm summits. a ^{10}Be exposure age for an erratic boulder at an altitude of 1156 m in the eastern Cairngorms, ~14 km east of the study area, indicates deglaciation at 15.9 ± 1.0 ka (e=1.6 mm/ka; recalculated from Phillips et al. (2006). Whilst this age overlaps slightly the ages for moraines from the study area, the age also allow final deglaciation of the Cairngorm tops to have occurred up to 1-2 ka before the final ice advance down Strath Spey. Granite boulders from the floor of upper Strath Nethy have provided recalculated ^{10}Be weighted mean ages, excluding outliers, of 16.9 ± 0.8 ka (e=0; recalculated from Ballantyne and Stone, 2013). The boulders accumulated by run out from major rock slope failures of cliffs onto the surface of glacier ice in upper Strath Nethy. Sloping, schist-bearing moraines extend from the M1 limit into Strath Nethy towards the margin of these boulder accumulations. Exposure ages for the boulder accumulations are older than for the M1 moraine, suggesting that rock slope failure in Strath Nethy occurred before abandonment of the M1 ice limit and supporting earlier deglaciation of the northern Cairngorm plateau.

Everest and Kubik (2006) provided ^{10}Be exposure ages on granite boulders resting on the Glen More and Gleann Einich moraines. As in the study area, a range of ages was obtained, individual sample exposure ages ranging from 17.3 ± 1.4 ka to 12.9 ± 1.1 ka (e=0; recalculated from Everest and Kubik, 2006) (Fig.4). The mean ages of 15.0 ± 0.7 ka for the Glen More moraine and of the 15.3 ± 0.7 ka for the Gleann Einich moraine however are statistically equivalent to mean ages of 15.0 ± 0.6 ka from moraines M1 and M3 in the study area (e=0; recalculated from Everest and Kubik, 2006). Rock slope failures in the Lairig Ghru occurred soon after meltwater flow had ceased through the Chalamain Gap meltwater channel with a floor that stands below the projected elevation of M1 limit. Surface boulders have provided recalculated total-uncertainty weighted mean ages of 16.0 ± 0.7 ka (e=0; recalculated from Ballantyne and Stone, 2013), again suggesting that rock slope failure occurred before the M1 readvance. OSL dates for lake sediments between moraines marking limits of Cairngorm and Spey ice in Glen Einich are significantly older at 16.7 ± 0.5 and 16.7 ± 5.4 cal ka BP (Everest and Golledge, 2004). An error weighted mean ^{10}Be exposure age for boulder on a moraine at an elevation of 362 m south of Newtonmore indicates deglaciation at 14.1± 0.6 ka (e=0; recalculated from Gheorghiu and Fabel, 2013). Two radiocarbon dates obtained for basal organic sediments in a kettle hole at Loch Etteridge (Fig. 1), 30-35 km up-valley from the study area (Sissons and Walker, 1974; Everest and Golledge, 2004) yielded an uncertainty-weighted mean age of 15.6 ± 0.3 cal. ka BP. Tephrostratigraphic evidence from the same site implies deglaciation prior to 14.0 ka and probably 14.5 ka (Lowe et al., 2008a). A kettle hole lake in Abernethy Forest (Fig. 1), 10 km north-west of the study area, has also provided a basal radiocarbon date of 14,764 ± 384 cal. a. (Vasari and Vasari, 1968). These radiocarbon dates postdate the final disappearance of glacier ice on the valley floor at these sites and so add support to the results from cosmogenic exposure dating.

Comparison of the dates in the study area with the detailed climatic record elaborated in the Greenland ice cores is shown in Figure 6. Advance to the M1 limit and subsequent deglaciation occurred towards the close of Greenland Stadial 2a (GS-2a) (16.9-14.7 ka) (Björck et al., 1998). Both the cosmogenic exposure ages on moraines and the radiocarbon ages of organic matter in kettle holes show that that deglaciation was already well underway by the start of the Lateglacial (Windermere) Interstadial at 14.7 ka. Indeed, the deglaciation occurred during a hemispheric climate that was relatively cool, if oscillating. The period of deglaciation at ~15.0 ka also appears to fall entirely within the 1.0 ka uncertainties of the ^{10}Be cosmogenic exposure ages and so indicates that final ice retreat was rapid. During this period, the ice margin on the flanks of Strath Spey was lowered from elevations of 830 m to <360 m and retreated up-valley over a distance of more than 60 km, requiring ice front recession at average rates of >60 m/a.

Rapid deglaciation requires that any stillstands of the ice margin were brief. In such a case it is necessary to explain the large volumes of sediment found in embayments along the south-eastern flank of Strath Spey. In lower Gleann Einich and in the Lairig Ghru, stream sections in large terraces expose thick sequences of glacial lake sediments that include thin, horizontal beds of sand and silt (Brazier et al., 1998). The large numbers of couplets, when interpreted as annual varves, suggest that Strath Spey ice blocked these valley exits for up to 1 ka (Everest and Kubik, 2006). Varve layers apparently amounting to several centuries of lake-bottom sediment accumulation have also been recognized in glacilacustrine sediment sequences on the Monadhliath flank of Strath Spey (Phillips and Auton, 2013). Interpretation of some of these couplets as varves however has been disputed (Brazier et al., 1998) and poor exposure makes relationships to contemporaneous ice fronts difficult to assess. To derive these large sediment volumes, it is unlikely that bedrock erosion beneath the glaciers at the time was a significant component as hillslopes between embayments show only small, intermittent moraine ridges. Factors favouring the build-up of thick sediments include an ice surface slope that directed ice flow towards the eastern flank of Strath Spey ice and ice flow lines that focused sediment supply towards embayments (Brazier et al., 1998; Golledge, 2002). The thicknesses of several tens of metres of glacifluvial and glacilacustrine gravel and sand found in many embayments probably requires however the reworking or over-riding of older sediments. Stream sections in large moraines and kame terraces in Abernethy Forest (Bremner, 1934a), below the Cairngorm Ski Car Park (Sugden, 1970) (Fig. 2C) and in Gleann Einich (Brazier et al., 1998; Golledge, 2002) each show a broadly similar, two-part stratigraphy. These sections are typically capped by several metres of till that overlies much thicker sequences of bedded gravel, sand and diamicton. Glacial deformation of the underlying sediment sequences (Golledge, 2002) and incorporation of rounded gravel- and sand-rich debris into the upper till are recurrent features, indicating that the minor ice advances to the limits marked by the moraine ridges each took place across thick, pre-existing sediments.

Rapid deglaciation occurred mainly as the Strath Spey ice lobe remained active. The off-lapping assemblages of moraines, marginal channels and kame terraces show that ice and meltwater continued to flow along and towards the flanks of Strath Spey even as the ice front retreated up-valley. In embayments such as that drained by Allt Bheadhair, east of the Nethy basin (Fig. 2), off-lapping sets of arcuate ridges occur at elevations between 300 and 700 m. Average ridge spacing is ~100 m and comparison with the mean rate of ice retreat of >60 m/a. proposed in this study allows the possibility that the ridges represent annual retreat moraines. Exceptions to the general model of active retreat probably include the ice in upper Strath Nethy that was left stagnant once the col at The Saddle (803 m) cut off the supply of ice from Glen Avon (Hinxman and Anderson, 1915). Also, the eskers, kames and kettle holes mapped on the floor of Strath Spey probably were formed in the final stages of ice-wastage (Hinxman and Anderson, 1915; Young, 1974, 1975; Young, 1978). Extensive dead ice held in the basins of mid Strath Spey is a feature of recent simulations of the final stages of decay of the last ice sheet in Scotland (Hubbard et al., 2009).

The dating constraints provided here provide a test for simulations of the last Scottish ice sheet that use a high-resolution glaciological model derived from by the NGRIP ice-core record time-series and modern climate gradients (Hubbard et al., 2009). Experiment E109b2bc suggests that, from 19.4 ka onwards, there was active, dynamic and extremely rapid thinning and retreat in the present offshore area of the outer Moray Firth in response to sustained warmer climatic conditions. Century to millennial scale oscillations reflected in the ice core are sufficient to drive cycles of glacier advance and retreat in the maritime Scottish ice sheet. A period of relative cooling after 17.4 ka stabilises a much reduced, thinner and mainly cold-based ice sheet over much of the uplands of north-east Scotland. By 15.7 ka, continued warming further reduces cover to an ice cap limited to the Western Highlands and the Cairngorms. After a final advance at 15.2 ka, ice cover is rapidly reduced, and the simulated extent of ice in Strath Spey fits that identified in this study by 14.6 ka. It is tempting to relate the field and dating evidence from our study site and its wider environs to this latter phase of advance and rapid retreat. However, there is an important caveat. Although the simulated timing is within error of the date of deglaciation proposed here, the regional ice cover depicted in the glaciological model is much greater than indicated by our morphological evidence for separation of Spey and Cairngorm ice by 15.0 ka.

Few other dating constraints exist for this period of deglaciation in the Grampian Highlands. The upper Dee valley became ice-free before 14.6 ka (Huntley, 1994), requiring that a series of ice margins identified down-valley (Fig. 1) are older features (Brown, 1993). A significant readvance of ice in the inner Moray Firth, the Elgin Oscillation (Fig. 1), occurred before ~14.9 ka (Peacock et al., 1968; Merritt et al., Submitted) at a time when large parts of lower Strath Spey were already ice-free. It is likely that the ice advance in mid-Strath Spey documented here was broadly coeval with this event. Reconstruction of the pattern of ice retreat for the entire British and Irish Ice Sheet places ice limits at 15 ka close to those proposed here (Clark et al., 2012). Rapid deglaciation between 15 and 16 ka is also indicated by cosmogenic exposure ages for the southern parts of the Fennoscandian (Larsen et al., 2012) and Laurentide (Davis et al., 2015) ice sheets.

Why should there have been an advance and rapid deglaciation at a time when the ice cores suggest a relatively cool, if oscillating, climate coinciding with the Greenland Stadial 2a? One possibility acknowledged by Hubbard et al (2009) is that the lag between glacier response and climate forcing on century to millennial time scales is that the glaciers are usually out of phase with climate. Following a lagged advance, the glacier finds itself at the maximum of an advance at a time of relative warmth and thus is vulnerable to rapid melting. An alternative hypothesis is that there were regional factors in Scotland that dominated the hemispheric climate signal, a point recognised by Clark et al. (2012) when commenting on the contrasts between the empirical record of ice sheet decay in the UK and predictions of models. The British-Irish Ice Sheet saw the collapse of its marine portions between 19 and 17ka and the ice sheet was confined to the mainland by 16 ka (Clark et al, 2012). The latter situation would be especially important for mainland Scotland in that warmer Atlantic water would replace ice immediately offshore to the west. Given westerly sources of precipitation, one would expect this new proximity to the sea to lead to a sharp increase in snowfall on the ice dome over Rannoch Moor. Given a climate that was still cool, the result would be an advance of land-based glaciers on the eastern margin of the ice sheet. But in time, overall hemispheric warming would triumph and lead to deglaciation. Perhaps also the rapidity of deglaciation reflects the location of the Spey ice lobe on the lee side of the ice sheet where it was subject to enhanced melting by Föhn winds, a situation that is characteristic of the comparable climate and topography of ice caps in Patagonia (Hulton and Sugden, 1995; Casassa et al., 2006).

CONCLUSIONS

Towards the close of the Late Devensian glaciation, an ice lobe advanced down Strath Spey to limits north of Grantown. Early unzipping from Cairngorm ice along the eastern margin of the lobe is recorded by ice-marginal meltwater channels, kame terraces and moraines found between Glen More and Strath Nethy. Correlative ice margins can be traced from ice-marginal features for 60 km up-valley into the Lairig Ghru and Gleann Einich and further on the Monadhliath flank of Strath Spey.

New cosmogenic ^{10}Be exposure ages for boulder samples for moraines at 740-540 m O. D. in the northern Cairngorms indicate deglaciation at 15.0 ± 0.6 ka. This timing matches existing age data for deglaciation of other sites along Strath Spey. Active ice retreat from the central Grampians was rapid and occurred within the ~1 ka uncertainty of the cosmogenic exposure ages. Comparison with Greenland ice core records indicates that ice advance and the onset of final ice retreat occurred at the close of Greenland Stadial 2a (GS-2a) (16.9-14.7 ka). Perhaps the advance was a response to increased precipitation following the loss of the marine parts of the British and Irish Ice Sheet west of the Scottish mainland.

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FIGURE LIST

Figure 1. Location map of the Grampian Mountains. The maximum extent of the Strath Spey ice lobe is shown. For comparison, the limits are shown of the Loch Lomond Stadial ice sheet in the western Grampians, the main stillstands during ice retreat in the Dee valley (Brown, 1993) and the Elgin Oscillation (Peacock et al., 1968). C Cairngorm; E Elgin Oscillation; M Monadhliath; R Rannoch Moor. Stars indicate the locations of radiocarbon-dated Lateglacial sites.

Figure 2. NextMap model of the eastern flank of mid-Strath Spey. The spur of Sròn a' Ch-no, in the centre of the Box indicating area of Fig 4, separates the Glenmore basin from Strath Nethy. The likely lateral extent of the M1-M3 ice limits shown. The dashed white line marks the northern edge of the Cairngorm Granite.

1. Strath Spey 2. Monadhliath flanks. 3. Glean Einich. 4. Lairig Ghru. 5. Coire an t-Sneachda. 6. Glen Avon. 7. Strath Nethy. 8. Sròn a' Cha-no. 9. Water of Caiplich. 10. Glen More. 11. Kincardine Hills. 12. Allt Bheadhair. 13. Abernethy Forest.

Stars indicate sites with cosmogenic exposure ages. Box indicates the area of Fig. 4.

Figure 3. Ice-marginal landforms in the northern Cairngorms.

A. View west across Strath Nethy.

B. View north-east from the Coire na Ciste Car Park.

C. View west from below the Coire Cas Car Park.

a. Lateral moraine. b. Marginal meltwater channel. c. Kame terrace d. Delta fan. e. Glacial trimline.

Figure 4. Geomorphological map of the area between Glen More and Strath Nethy. Modified after Brazier et al. (1996).

1. Moraine ridge. 2. Fan or kame terrace. 3. Boulders accumulations derived from rock slope failures. 4. Cliff. 5. Ice-contact slope. 6. Glacial drainage channel. 7. Tor. 8. Sites with cosmogenic exposure ages.

Figure 5. Elevations of ice-marginal landforms along mid-Strath Spey and their relationship to the M1 and M3 moraine limits. YD = Younger Dryas moraines; LE = Loch Etteridge; AF = Abernethy Forest

Figure 6. Dates constraining final deglaciation of the Cairngorms compared to the GISP2 and GRIP Greenland ice cores and stadial/interstadial events. The radiocarbon and most

cosmogenic dates imply that rapid deglaciation took place before the warming represented by the Windermere interstadial.

TABLE LIST

Table 1. Sampling sites for ^{10}Be surface exposure dating

Table 1				
Sample ID	Altitude (m)	Grid reference	Moraine	Site description
CG12-001	737	NJ 01362 08262	M1	Unweathered, coarse-grained granite boulder, 1 m high, resting on schist bedrock.
CG12-002	739	NJ 01366 08279	M1	Large coarse-grained granite block on schist
CG12-003	740	NJ 01376 08248	M1	Granite bedrock sample from top of cliff at side of meltwater channel
CG12-004	735	NJ 01289 08083	M1	Quartz vein projecting from hydrothermally-altered granite
CG14-001	741	NJ 01158 07369	M1	Flat-topped granite boulder, 4 x 4 x 2 m, above general slope of ~30 degrees. Sampled 1 cm thick surface chippings.
CG14-002	723	NJ 01035 07392	M1	Large granite boulder on smooth slope of ~20 degrees. 4 x 3 x 2 m size. Sampled 3 cm thick surface chippings.
CG14-003	603	NJ 00781 07811	M2	Upstanding quartz veins on psammite boulder, 2 x 2 x 2 m. Quartz veins sampled are up to 4 cm above more eroded schist surface. Sample thickness ~3 cm on average.
CG14-004	546	NJ 00513 08366	M3	Granite boulder 1 x 1 x 1 m. Boulder rises 50 cm above ridge top. Sampled 1 cm thick surface chippings.
CG14-005	540	NJ 00311 07888	M3	Granite boulder 2 x 1.5 x 0.5 m. Sample is ~3cm thick.

All samples were from coarse-grained feldspathic granite, except CG12-004 and CG14-003, which were from vein quartz.

Table 2. Cosmogenic ^{10}Be surface exposure ages

Sample ID	Lat (DD)	Long (DD)	Elevation (m)	Sample thickness (cm)	Topographic shielding correction	^{10}Be concentration (x10^3 at/g)	1σ concentration uncertainty (x10^3 at/g)	Age (years, Du scaling)	1σ age internal uncertainty (years)	1σ age external uncertainty (years, Du scaling)
CG12-001	57.15459	-3.63217	737	2.0	1.000	126.4	6.0	14710	710	880
CG12-002	57.15475	-3.63211	739	5.0	1.000	121.7	6.1	14470	740	900
CG12-003	57.15447	-3.63194	740	1.0	1.000	122.6	5.3	14110	620	800
CG12-004	57.15297	-3.63331	735	4.5	1.000	142.6	7.3	16650	850	1030
CG14-001	57.14653	-3.63519	741	2.0	0.907	186.0	7.1	23980	950	1280
CG14-002	57.14671	-3.63723	723	3.5	0.959	132.1	5.1	16440	650	870
CG14-003	57.15042	-3.64160	603	1.5	0.972	117.5	5.0	15780	680	890
CG14-004	57.15534	-3.64624	546	1.0	0.976	96.97	4.12	13550	580	760
CG14-005	57.15101	-3.64939	540	3.5	0.974	106.7	4.5	15360	660	860

REFERENCES

Balco, G, Stone, JO, Lifton, NA, Dunai, TJ, 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quaternary Geochronology* **3**: 174-195.

Ballantyne, CK, 2010. Extent and deglacial chronology of the last British-Irish Ice Sheet: implications of exposure dating using cosmogenic isotopes. *Journal of Quaternary Science* **25**: 515-534.

Ballantyne, CK, Schnabel, C, Xu, S, 2009. Exposure dating and reinterpretation of coarse debris accumulations ("rock glaciers") in the Cairngorm Mountains, Scotland. *Journal of Quaternary Science* **24**: 29–31.

Ballantyne, CK, Stone, JO, 2012. Did large ice caps persist on low ground in north-west Scotland during the Lateglacial Interstade? *Journal of Quaternary Science* **27**: 297-306.

Barrow, G, Hinxman, LW, Craig, EHC, 1913. *The geology of upper Strathspey, Gaick and the Forest of Atholl*. HMSO, Edinburgh p. 112.

Binnie, SA, Dunai, TJ, Voronina, E, Goral,T, Heinze, S, Dewald, A, 2015. Separation of Be and Al for AMS using single-step column chromatography. *Nuclear Instruments and Methods in Physics Research Section B* **361**: 397–401.

Björck, S, Walker, MJ, Cwynar, LC, Johnsen, S, Knudsen, KL, Lowe, JJ, Wohlfarth, B, 1998. An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE group. *Journal of Quaternary Science* **13**: 283-292.

Boston, CM, 2013. *Regional and local plateau ice fluctuations during the last Glacial-Interglacial Transition: ice-dammed lakes and local readvances in the southeast of the Monadhliath Mounatins*, In: Boston, C., Lukas, S., Merritt, J. (Eds.), The Quaternary of the Monadhliath Mountains and the Great Glen: field guide. Quaternary Research Association. Quaternary Research Association, pp. 197-204.

Brazier, V, Gordon, JE, Kirkbride, MP, Sugden, DE, 1996. *The Late Devensian ice sheet and glaciers in the Cairngorm Mountains*, In: Glasser, N.F., Bennett, M.R. (Eds.), The Quaternary of the Cairngorms. Quaternary Research Association, London, pp. 28-53.

Brazier, V, Kirkbride, M, Gordon, JE, 1998. Active ice-sheet deglaciation and ice-dammed lakes in the northern Cairngorm Mountains, Scotland. *Boreas* **27**: 297-310.

Bremner, A, 1934a. The glaciation of Abernethy Forest. *Transactions of the Edinburgh Geological Society* **13**: 1-16.

Bremner, A, 1934b. The glaciation of Moray and ice movements in the north of Scotland. *Transactions of the Edinburgh Geological Society* **13**: 17-56.

Brown, IM, 1993. Pattern of deglaciation of the last (Late Devensian) Scottish ice sheet: evidence from ice-marginal deposits in the Dee valley, northeast Scotland. *Journal of Quaternary Science* **8**: 235-250.

Casassa, G. Rivera, A, Schwikowski, M, 2006. Glacier mass balance data for southern South America (30^{o}-56^{o} S) In Knight, PG, (Ed) *Glacier Science and Environmental Change*, Oxford. Blackwell, 239-241.

Charlesworth, JK, 1956. The Lateglacial history of the Highlands and Islands of Scotland. *Transactions of the Royal Society of Edinburgh* **62**: 769-929.

Clark, CD, Hughes, ALC, Greenwood, SL, Jordan, CJ, Sejrup, H-P, 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews* **44**: 112-146.

Davis, PT, Bierman, PR, Corbett, LB, Finkel, RC, 2015. Cosmogenic exposure age evidence for rapid Laurentide deglaciation of the Katahdin area, west-central Maine, USA, 16 to 15 ka. *Quaternary Science Reviews* **116**: 95-105.

Dewald, A, Möller, O, Petkov, P, 2012. Developing the Recoil Distance Doppler-Shift technique towards a versatile tool for lifetime measurements of excited nuclear states. *Progress in Particle and Nuclear Physics* **67**: 786-839.

Dunai, T, 2001. Influence of secular variation of the geomagnetic field on production rates of *in situ* produced cosmogenic nuclides. *Earth and Planetary Science Letters* **193**: 197-212.

Everest, JD, Golledge, NR, 2004. *Dating deglaciation in Strathspey and the Cairngorm Mountains*, In: Lukas, S., Merritt, J.W., Mitchell, W.A. (Eds.), The Quaternary of the Central Grampian Highlands. Quaternary Research Association, London, pp. 50-57.

Everest, JD, Kubik, PW, 2006. The deglaciation of eastern Scotland: cosmogenic ^{10}Be evidence for a Lateglacial stillstand. *Journal of Quaternary Science* **21**: 95-104.

Gheorghiu, DM, Fabel, D, 2013. *Revised surface exposure ages in the southeast part of the Monadhliath Mounatins, Scotland*, In: Boston, C., Lukas, S., Merritt, J. (Eds.), The Quaternary of the Monadhliath Mountains and the Great Glen: field guide. Quaternary Research Association. London, pp. 183-190.

Gheorghiu, DM, Fabel, D, Hansom, JD, Xu, S, 2012. Lateglacial surface exposure dating in the Monadhliath Mountains, Central Highlands, Scotland. *Quaternary Science Reviews* **41**: 132-146.

Golledge, N, 2002. Glaci-tectonic deformation of proglacial lake sediments in the Cairngorm Mountains. *Scottish Journal of Geology* **38**: 126-136.

Gordon, JE, 1993. *The Cairngorms*, In: Gordon, J.E., Sutherland, D.G. (Eds.), Quaternary of Scotland. Chapman and Hall, London, pp. 259-276.

Greenwood, SL, Clark, CD, Hughes, AL, 2007. Formalising an inversion methodology for reconstructing ice-sheet retreat patterns from meltwater channels: application to the British Ice Sheet. *Journal of Quaternary Science* **22**: 637-645.

Hall, AM, Phillips, WM, 2006. Glacial modification of granite tors in the Cairngorms, Scotland. *Journal of Quaternary Science* **21**: 811-830.

Hinxman, LW, Anderson, EM, 1915. *The geology of mid-Strathspey and Strathdearn*. *Memoir Geological Survey of Scotland*. HMSO, Edinburgh.

Hinxman, LW, Teall, JJH, 1896. The geology of West Aberdeenshire, Banffshire, parts of Elgin and Inverness. *Memoir Geological Survey of Scotland*. HMSO, Edinburgh.

Hubbard, A, Bradwell, T, Golledge, NR, Hall, AM, Patton, H, Sugden, DE, Cooper, R, Stoker, MS, 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. *Quaternary Science Reviews* **28**: 758-776.

Hulton, NRJ, and Sugden, DE, 1995. Modelling mass balance on former maritime ice caps: a Patagonian example. *Annals of Glaciology*, **21**, 304-310.

Huntley, B, 1994. Late Devensian and Holocene palaeoecology and palaeoenvironments of the Morrone Birkwoods, Aberdeenshire, Scotland. *Journal of Quaternary Science* **9**: 311-336.

Larsen, NK, Linge, H, Håkansson, L, Fabel, D, 2012. Investigating the last deglaciation of the Scandinavian Ice Sheet in southwest Sweden with ^{10}Be exposure dating. *Journal of Quaternary Science* **27**: 211-220.

Merritt, J, Connell, ER, Hall, AM, Riding, J, Submitted. Middle to Late Devensian glaciation of north-east Scotland: implications for the north-eastern quadrant of the last British ice sheet. *Journal of Quaternary Science*.

Merritt, JW, Auton, CA, Boston, CM, Everest, JD, Merritt, JE, 2013. *An overview of the main Late Devensian glaciation of the Central Grampian Highlands*, In: Boston, C., Lukas, S., Merritt, J. (Eds.), The Quaternary of the Monadhliath Mountains and the Great Glen: field guide. Quaternary Research Association. London, pp. 25-40.

Nishiizumi, K, Imamura, M, Caffee, MW, Southon, JR, Finkel, RC, McAninch, J, 2007. Absolute calibration of 10 Be AMS standards. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **258**: 403-413.

Peacock, JD, Berridge, NG, Harris, AL, May, F, 1968. *The geology of the Elgin District*. *Memoir of the Geological Survey*. HMSO, Edinburgh p. 155.

Phillips, ER, Auton, CA, 2013. *Evidence for active ice retreat and ice-dammed lake formation during deglaciation in Raitts Burn*, In: Boston, C., Lukas, S., Merritt, J. (Eds.), The Quaternary of the Monadhliath Mountains and the Great Glen: field guide. Quaternary Research Association. London, pp. 153-163.

Phillips, WM, Hall, AM, Mottram, R, Fifield, K, Sugden, DE, 2006. Cosmogenic exposure ages of tors and erratics on the Cairngorm plateau, Scotland: timescales for the development of a classic landscape of selective linear glacial erosion. *Geomorphology* **73**: 222-245.

Sissons, JB, Walker, MJC, 1974. Lateglacial site in the central Grampian Highlands. *Nature* **249**: 822-824.

Small, D, Fabel, D, 2015. A Lateglacial ^{10}Be production rate from glacial lake shorelines in Scotland. *Journal of Quaternary Science* **30**: 509-513.

Sugden, DE, 1970. Landforms of deglaciation in the Cairngorm Mountains, Scotland. *Transactions of the Institute of British Geographers* **51**: 201-219.

Sugden, DE, Clapperton, CM, 1975. *The deglaciation of upper Deeside and the Cairngorm Mountains*, In: Gemmell, A.M.D. (Ed.), Quaternary Studies in North East Scotland. Aberdeen University., Aberdeen, pp. 30-38.

Vasari, Y, Vasari, A, 1968. Late- and Post-Glacial macrophytic vegetation in the lochs of northern Scotland. *Acta botanica fennicae* **45**: 193-217.

Young, JAT, 1974. Ice wastage in Glenmore, upper Spey Valley, Inverness-shire. *Scottish Journal of Geology* **10**: 147-158.

Young, JAT, 1975. A re-interpretation of the deglaciation of Abernethy Forest, Inverness-shire. *Scottish Journal of Geology* **11**: 193-205.

Young, JAT, 1977. Glacial geomorphology of the Dulnain valley, Inverness-shire. *Scottish Journal of Geology* **13**: 58-74.

Young, JAT, 1978. The landforms of upper Strathspey. *Scottish Geographical Magazine* **94**: 76-94.

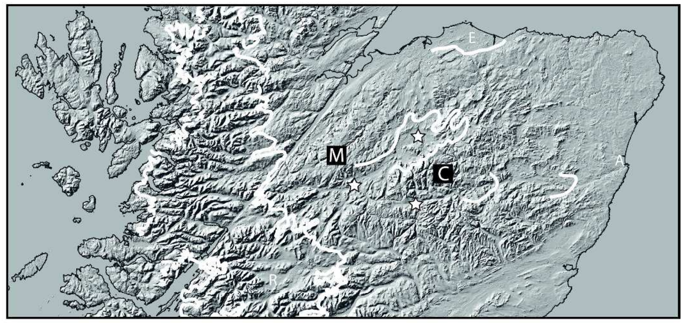

Fig. 1
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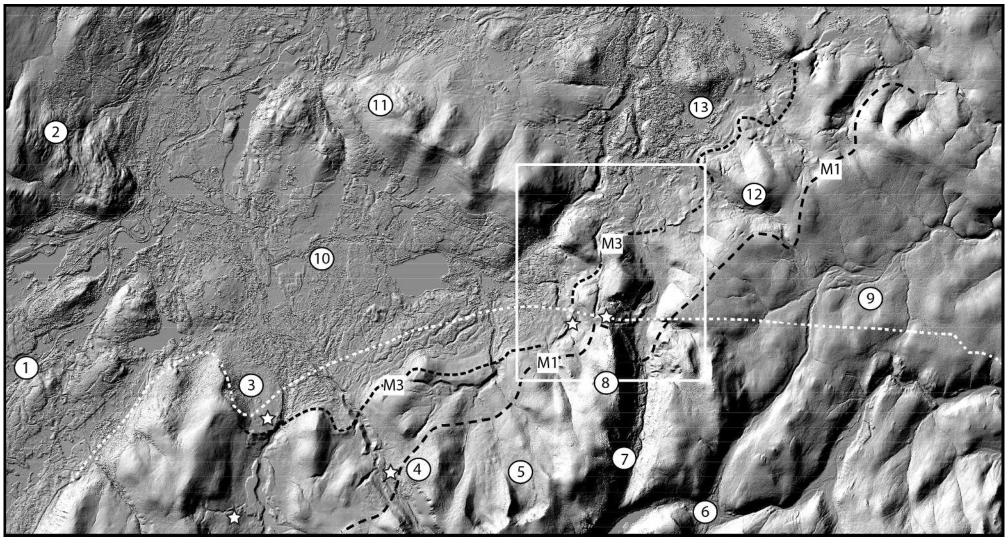

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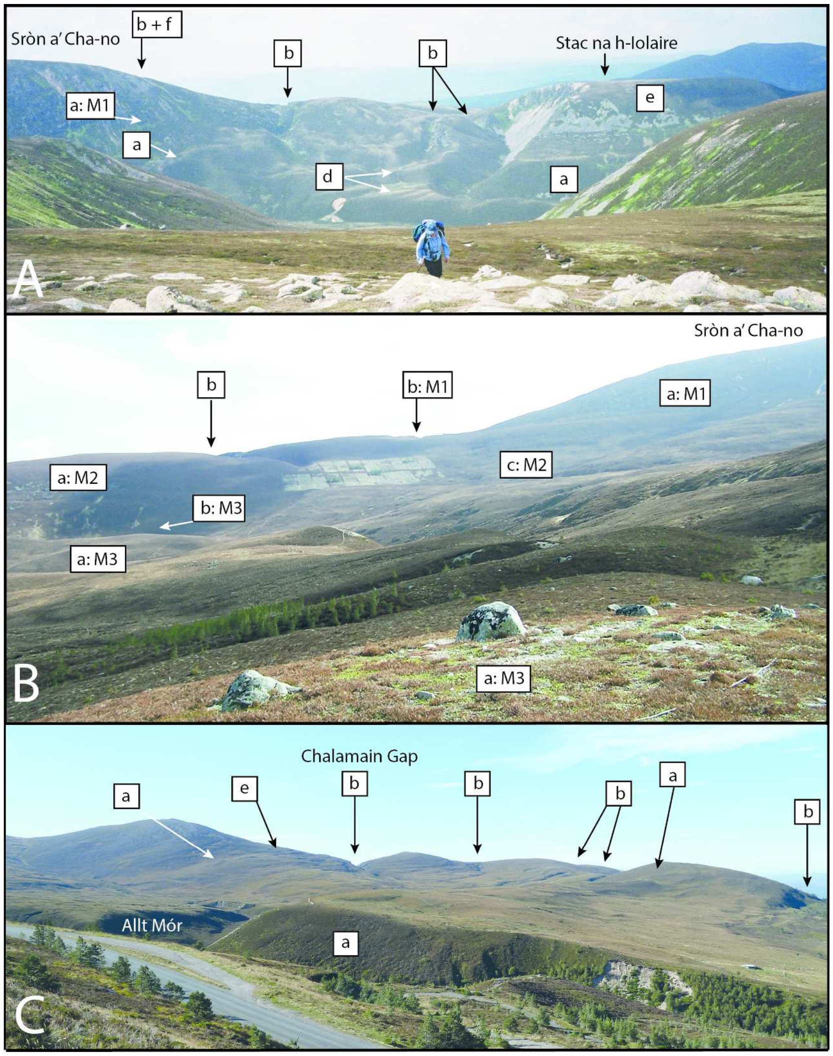

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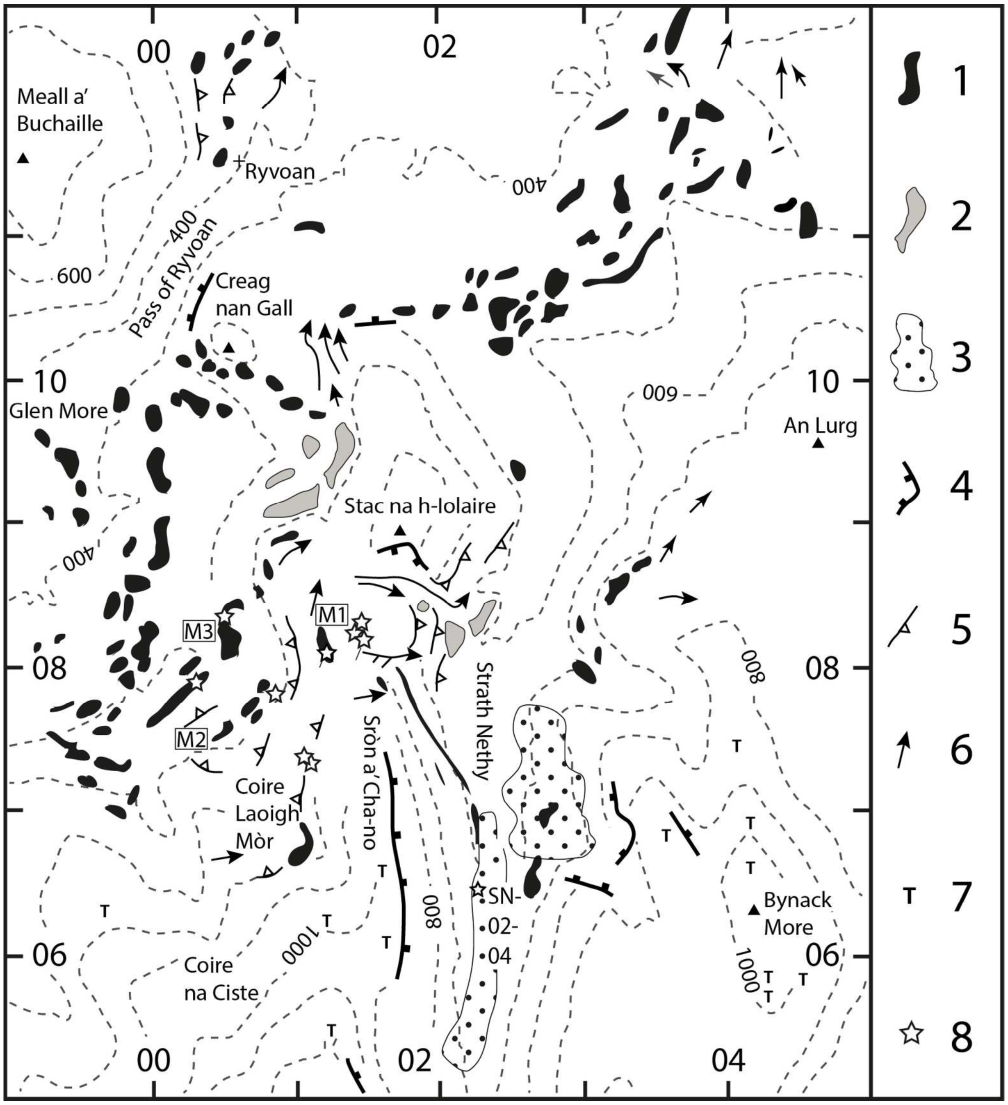

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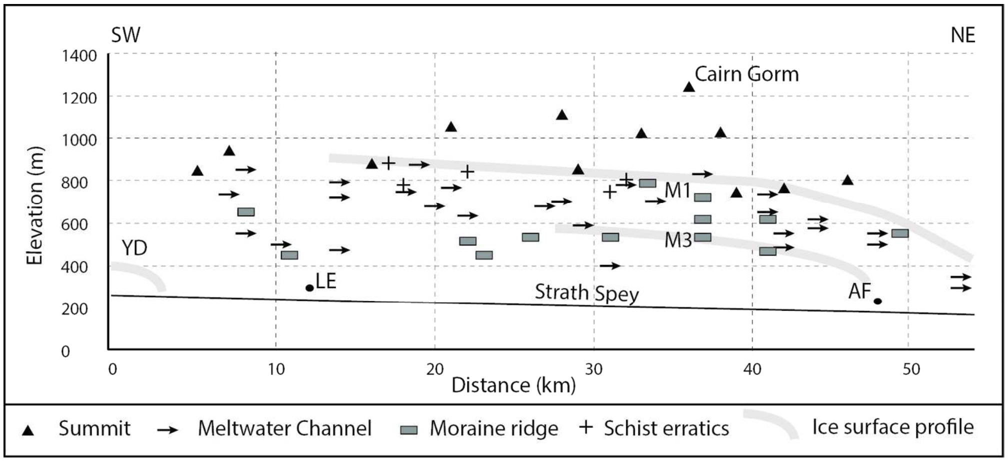

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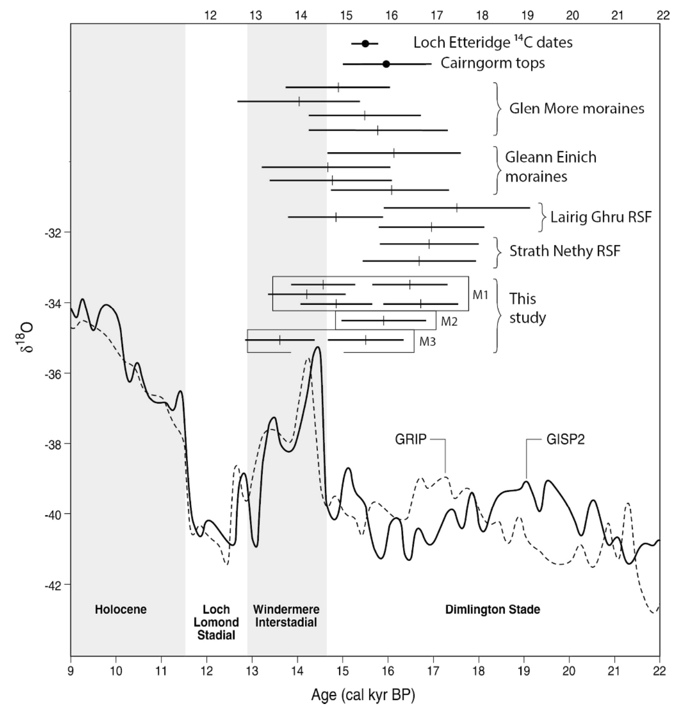

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